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Analysis of the impacts of retrofit actions on the life cycle energy consumption of typical neighbourhood dwellings

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ABSTRACT

The residential sector is one of the most significant energy consumers and therefore contributes significantly to climate change. A study of not only the use of energy during the operation but also the associated consumption and emissions in the life cycle is required. One way to reduce life cycle energy consumption is through retrofitting existing buildings. This study analysed the energy consumption and its greenhouse gas emissions after applying five sustainable retrofit measures. For this purpose, two typical neighbourhood dwellings were chosen, located in the city of Vitória, in the state of Espírito Santo, Brazil. The analysis was conducted for the pre-operational and operational stages. Using pre-established standards, the energy of the building materials that compose the dwellings was calculated as well as the consumed operational energy. The labelling of the building envelopes was also verified, according to the simulation method specified by the Technical Quality Requirements for Energy Efficiency Levels of Residential Buildings (RTQ-R). The software programme used to calculate performance was EnergyPlus. The results indicated that adopting all retrofit measures yielded improvements in the life cycle for only one building, namely, a 15% reduction in energy consumption and a payback time of 10.4 years. Although these results are lower than those reported in some international studies, the analysis showed significant improvements in the operational stage of both buildings, in both labelling and energy consumption.

1. Introduction

Buildings account for approximately 30–40% of worldwide energy consumption and have a higher carbon footprint than the transportation sector [1]. To stabilize the CO_2 concentration levels set by the International Energy Agency (IEA), buildings must reduce their direct and indirect greenhouse gas emissions at least 38% by 2050 [1].

In Brazil, the energy consumption of buildings follows the world trend, accounting for approximately 42.5% of electricity consumption (21.2% by the residential sector, 14.5% by the commercial sector and 6.8% by the public sector) [2]. These consumption figures have motivated government agencies to develop standards and procedures for regulating the construction and operation of new buildings. However, one way to reduce energy consumption is through retrofitting existing buildings. The Brazilian standard defines a retrofit as the "remodelling or upgrade of building systems through the inclusion of new technologies and concepts in order to increase property value and lifetime, to adapt to a new usage and to improve operational and energy efficiency" ([3], page 09). Therefore, several retrofit actions involve remodelling buildings and incorporating new technologies to make them more energy efficient.

One way to measure environmental impacts from the production of a given product is the Life Cycle Assessment (LCA). According to John [4], LCA is the only tool that enables a systemic impact analysis, which identifies and quantifies the input and emission flows at all stages of the product life cycle. This methodology can be applied to any product and service, including buildings. LCA studies for buildings began in the 1980s and increased in the 1990s, when discussion groups were organized to standardize the methodology, and the publications of scientific studies increased significantly [5].

The complexity of the processes related to LCA is a limitation of the tool's wide use for buildings. Several studies attempt to make the LCA methodology more accessible by incorporating it into 3D modelling with the BIM (Building Information Modelling) platform. Soust-Verdaguer et al. [6] have identified that the most common integration of BIM into LCA is the extraction of materials quantities from the 3D model and that higher levels of integration, such as the development of automated processes, remains limited. Wong and Zhou [7] identified only 8 papers that focused on the development of BIM-based tools for managing environmental performance during buildings retrofitting.

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The authors also suggested future research on the integration of BIM system with facility management, and the incorporation of the concept "reduce, reuse and recycle" on BIM sustainability analysis.

Within the development of the LCA for buildings, a new type of assessment tool, Life Cycle Energy Assessment (LCEA), focuses on the environmental impacts from energy consumption.

Like the LCA, the LCEA seeks to quantify the environmental impacts, albeit only from the perspective of energy production and consumption that is necessary for the manufacturing of building materials (embodied energy), the installation of construction works, operations (operational energy), maintenance (recurrent embodied energy), demolition, recycling and eventual transportation between stages [8].

Studies indicate that the life cycle stage of the building that consumes the most energy is the operational stage, for instance, operating refrigeration/heating appliances and artificial lighting, among other electrical appliances, and that the total energy required throughout the building life cycle accounts for little of the embodied energy of materials [8]. However, LCEA results vary by the region where the building is installed. [9] compared the LCA of two single-family homes, one located in Spain and another in Colombia. The results showed that, in the stage of use, the home in Colombia emits 73% fewer CO_2 emissions than the residence in Spain. TAVARES, [10], a pioneer of LCEA studies of buildings in Brazil, concluded that the range of life cycle energy consumption is approximately 15.01 GJ/m^2 to 24.17 GJ/m^2. These values are considered low compared with consumption in developed countries, where the values are between 50 GJ/m^2 and 90 GJ/m^2. The embodied energy of the materials in the life cycle was approximately 29–49%, a significant percentage when compared to international studies [10]. Ghattas et al. [11] found that the use stage represents between 45% and 95% of the total energy consumed throughout the life cycle. This variation owes to differences in design, geographical location and the period of analysis. This percentage decreases as the energy performance of the building increases, and the choice of building materials plays a decisive role in this situation [11]. A similar conclusion was obtained by Buyle et al. [5], who observed that if the operational energy in the use stage of the building decreases, the embodied energy of the building materials increases.

In the LCEA of retrofitted buildings, the incorporation of materials in the retrofit process generates an increase in embodied energy. However, this increase assists the thermal performance of the building, decreasing the energy consumption in the operational stage. This result was the conclusion of Bin and Parker [12], whose proposal of adding thermal insulation to the envelope of a building increased the total embodied energy of the materials by 51%. However, the addition also reduced the energy required for heating by 90%. Even though retrofit measures have proven effective in reducing environmental impacts [13], several studies suggest that research using the LCA approach in retrofitting buildings remains rare and requires further development [13–16].

The operation stage focuses primarily on reducing energy consumption. A Brazilian government initiative that encourages conscious energy consumption is the Brazilian Building Labelling Programme (PBE Edifica), which classifies residential, commercial and public buildings at levels ranging from "A" (more efficient) to "E" (less efficient). It is already mandatory to obtain the level "A" seal for new public buildings or those that undergo the retrofit process [17]. The analysis can be completed in a prescriptive manner, based on worksheets provided by the PBE Edifica or by simulation, namely, with the use of performance calculation software. EnergyPlus is a software programme that fulfils all requirements of the labelling programme, such as being assessed by ASHRAE [18] and modelling 8760 h per year. The performance improvement initiatives are of paramount importance to make the construction industry aware of measures that prioritize construction quality, thereby associating the reduction of energy consumption with user comfort. The retrofit has this purpose and therefore requires a better analysis of its benefits, while considering all the life cycle stages of the building.

This study therefore aimed to analyse the energy consumption and the respective greenhouse emissions of the energy life cycle following the application of sustainable retrofit measures in two typical neighbourhood buildings located in the city of Vitoria, in the state of Espírito Santo, Brazil. The analysis was conducted for the pre-operational and operational stages. The initial embodied energy (IEE) required to extract and fabricate materials, the recurrent embodied energy (REE) required to maintain and replenish materials and the embodied waste energy (IWE) were calculated with the loss rates corresponding to the construction and installation of the building materials. The energy consumption required for appliances, water heating, lighting and air conditioning was also calculated. The envelope efficiency labels of the buildings were verified, according to the simulation method specified by the PBE Edifica.

2. Case study

A study performed by Giacomin [19] outlined the main typologies of multifamily residential buildings in the neighbourhood of Jardim Camburi (20°15′39″ S, 40°15′59″ W) located in the city of Vitória, state of Espírito Santo, Brazil. According to the Brazilian Bioclimatic Zoning [20], the region is in zone ZB8, characterized by a hot and humid climate throughout the year. The study was based on the number of floors, with or without a balcony, as it is an important element of shading. Fig. 1 shows an aerial image of the neighbourhood Jardim Camburi and identifies the location and quantity of buildings of each type. In total, 663 multifamily residential buildings were identified. Of these, approximately 57% are buildings (marked in blue) that have between six and 12 floors with a balcony. Also noticeable is the concentration of buildings between four and five floors (marked in green and yellow, respectively) in a certain area, where the oldest buildings are and where the neighbourhood was first settled. The newest buildings are identified with red. These buildings have 15–22 floors and are located near each other, along the main avenue that bounds the neighbourhood. For each type, Giacomin [19] selected a representative building.

For this study, the two extremes of the building types were analysed, that is, a building type of four and five floors without a balcony (Building 1) and a building type of 15–22 floors (Building 2). As highlighted in Fig. 4, the two buildings are very different, not only in shape and number of floors but also in the year of construction and the building standard.

The first building, whose project was approved in 1981, has three standard floor plans on pilotis with no balcony, with eight housing units (HU) per floor. Each HU has two bedrooms and two bathrooms, with an area of 58.8 m^2. The second building, whose project was approved in 2014, has 17 standard floor plans on top of garage floors and pilotis. The apartments have balconies, and the top floor consists of duplex penthouses. Each floor has four HU, with four bedrooms and four bathrooms. The HU are between 138.0 m^2 and 154.7 m^2 in area. Although the two buildings differ significantly, the vertical seal of both is made of ceramic block, and the structure is made of reinforced concrete.

3. Methodology

According to Fig. 2, this paper made two simultaneous analyses: envelope performance and LCEA. The envelope performance was evaluated based on the Technical Quality Requirements for Energy Efficiency Levels of Residential Buildings – RTQ-R [30], that establishes the analysis when the buildings are naturally ventilated and artificially cooled.

Vilches et al. [13] after a review on LCA of building refurbishment, indicated that most of the papers drawn their conclusions from the comparison between operational and embodied energies. Therefore, for the LCEA, the methodology was divided into two parts, referring to the embodied energy (pre-operational stage) and operational energy

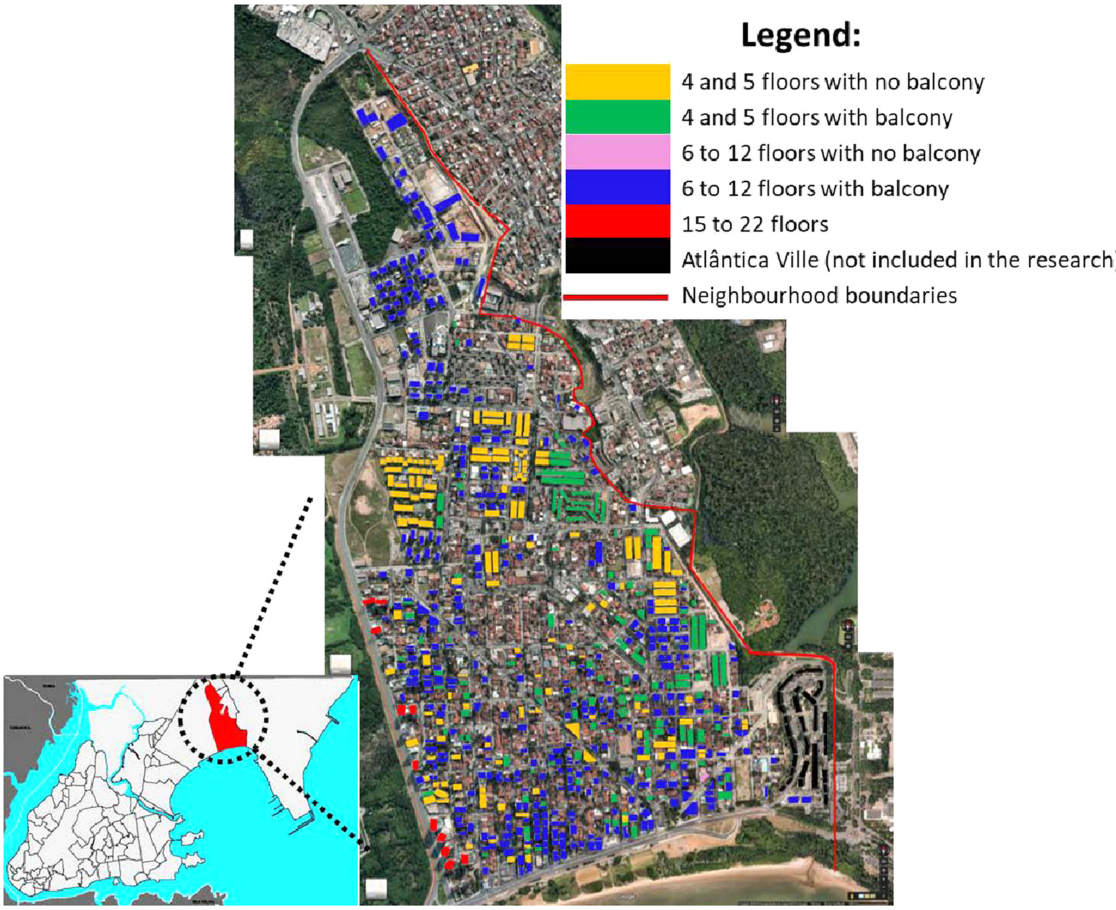


Fig. 1. Aerial image of Jardim Camburi.
Source: GIACOMIN [19].

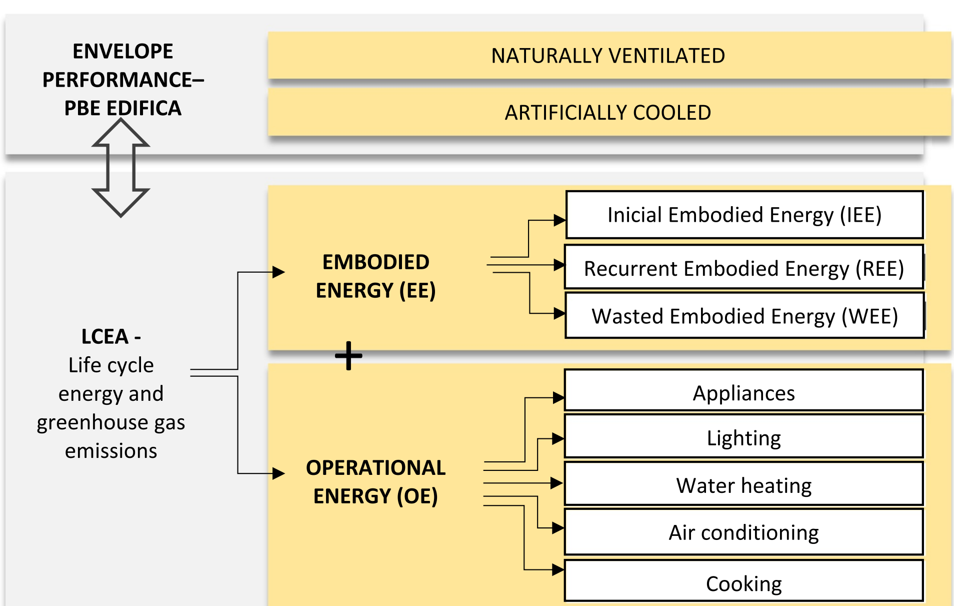


Fig. 2. Methodology summary.

(operational stage). First, the envelope performance, energy consumption and CO_2 emissions of the buildings were calculated as they are now, and the impacts of the retrofit proposals were then determined. For the LCEA, the steps considered in this study is presented in Fig. 3. The construction and demolition stages as well as transport between stages, were not considered due to the inaccuracy of available data required to calculate the energy consumption for those steps.

The total energy consumed in the life cycle of the buildings equals

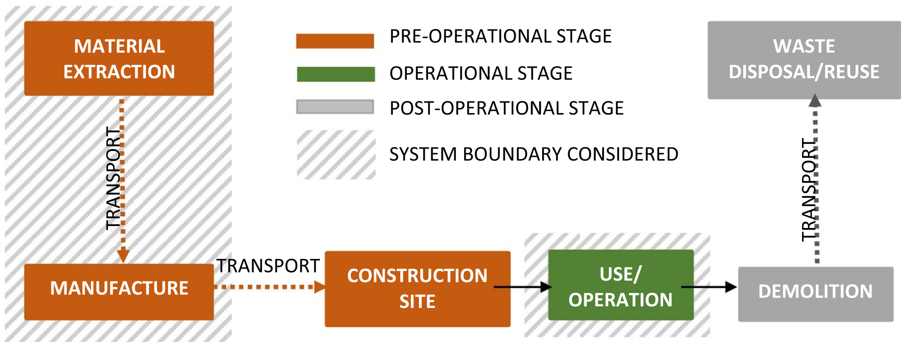


Fig. 3. Limits of the system considered in the study.

Table 1
Equations for calculation of Embodied Energy (EE).

$EE = \sum IEE + REE + WEE$		
$IEE = \sum m_i.\ M_i$	$REE = \sum m_i.\ M_i.(F_r - 1)$	$WEE = \sum (IEE + REE).\ F_l$

Note: EE = Total Embodied Energy (MJ); IEE = Initial Embodied Energy (MJ); REE = Recurrent Embodied Energy (MJ); WEE = Wasted Embodied Energy (MJ); m_i = quantity of material (kg); M_i = IEE value per unit of material (MJ/kg); F_r = Replacement factor; F_l = Loss factor (%).

the sum of the energy embodied in the pre-operational stage and the energy consumed in the operational stage.

The retrofit proposals were selected to provide improvements in thermal performance, considering the envelope as the main vector. The feasibility of the proposals was also considered with respect to the ease of installation and maintenance, with minimal interference in the aesthetics of the façade. We avoided interfering in the internal environments and the consumption habits of the inhabitants because these factors are difficult to control in multi-family dwellings. Therefore, the buildings were simulated in seven different situations, considering the following five retrofit proposals:

1. Existing building;
2. Replacement of the existing roof with a green roof: The green roof considered was the Light Alveolar Modular System [21], because, like the name suggests, it has light weight and it is recommended to roofs where the traffic is restricted;
3. Installation of reflective film on the glass panes of windows and sliding doors: The reflective film works as a filter to control the entrance of solar radiation;
4. Brise-soleil for shading the openings: The Brise-soleil controls the incidence of solar radiation. The system chosen is a 45° fixed-angle brise-soleil consisting of panels made of aluminium sheet [22];
5. Decreased absorptance of the opaque surfaces of the envelope (walls and cover): It was simulated on the envelope painted with light colours, such as white, ivory or beige, with absorptance of 0.2;
6. Installation of ventilated façade: The ventilated façade creates a layer of air between the surface of the main façade and the coating material. The system is composed of a layer of thermal insulation and concrete panels for sealing, which are fixed with light steel frames [23];
7. All the above retrofit actions.

We also analysed the behaviour of existing buildings in the life cycle and when all retrofit measures were simultaneously applied.

3.1. Embodied Energy of materials

The Embodied Energy (EE) of materials is the sum of Initial Embodied Energy (IEE), required for extraction and manufacture of the

Fig. 4. Image and 3D model of the case study. *Note: A = Image of buildings; B = 3D model of buildings.*

Table 2
Values used to calculate the EE and EC of the building materials.

	Density (kg/m^3)	EE (MJ/kg)	EC (kgCO$_2$/kg)	DL (years)	F_r	F_l
Steel	7850	30.00	2.31	73	1.00	10%
Aluminium	2700	210.00	9.15	30	1.67	0%
Concrete	2300	1.20	0.09	75	1.00	9%
Fibre-cement	1900	6.00	0.42	30	1.67	19%
Copper (electrical inst.)	8933	75.00	3.17	30	1.67	25%
Brass (hydro. inst.)	8530	80.00	3.38	30	1.67	20%
Wood	650	7.50	0.52	12	4.17	0%
PVC	1300	80.00	4.20	30	1.67	20%
Plaster	2000	1.47	0.11	60	1.00	13%
Ceramic brick	1400	2.90	0.23	60	1.00	17%
Paint	1300	65.00	4.49	12 (external)	4.17	16%
				4 (internal)	12.50	
Ceramic tile	2050	5.10	0.26	20	2.50	16%
Mortar laying	1860	2.10	0.16	20	2.50	18%
Glass	2500	18.50	0.89	30	1.67	0%
Waterproof lining[a]	1125	52.90	0.48	10	5.00	0%
Stone wool[a]	64	16.60	1.22	50	1.00	0%
Steel frame[a]	7850	33.8	1.63	50	1.00	0%
Glass PET film[a]	1380	186.40	6.92	25	2.00	20%

EE = embodied energy per kg of material; EC = embodied carbon per kg of material; DL = Design lifespan; F_r = Replacement factor; F_l = Loss factor.
Note:.
[a] EE and EC values extracted from SimaPro.

materials; Recurrent embodied Energy (REE), required for maintenance; and Wasted Embodied Energy (WEE), calculated from the material loss rates at the site [38]. Table 1 shows the equations used for calculating the Total Embodied Energy (EE).

The tool used to calculate the material quantity (m_i) was the ArchiCAD 3D modelling software [24], which uses the Building Information Modelling (BIM) platform to extract information from the building in a table format. Fig. 4 shows the 3D model, which was based on the design specifications, modelling the internal and external masonry, the structural elements, wooden doors, window frames, metal guardrails and the internal finishing. All other elements, such as the steel, foundation materials and other facilities, were estimated.

For the foundation, an index of 0.12 m^3 of concrete per m^2 of constructed area was used. This index was taken from a project whose foundation quantities were known. For the steel in the structure and foundation, an average steel demand of 91.68 kg per m^3 of concrete was used [25].

The quantity of materials for electrical and hydro-sanitary installations was estimated using a reference building from the study of Vechi and Ghisi [26]. Thus, the volume of material required for Buildings 1 and 2 is proportional to that of the reference building in terms of both area and number of bathrooms.

To calculate the REE, the lifespan of the building was set to 50 years. For the lifespan of the materials, the Maximum Design Lifespan (MDL) was established by NBR 15575 [3]. The replacement factor (F_r) is the ratio of the lifespan of the building to that of the material.

To calculate WEE, the loss rates were extracted from Agopyan et al. [27] and the Price Composition Tables [25].

After calculating the EE, the Embodied Carbon (EC) related to the carbon dioxide emissions associated with the energy consumption during the material process production was also calculated.

Table 2 shows the values considered for each building material density (kg/m^3), EE (MJ/kg), EC (kgCO$_2$/kg), DL (years), F_r and F_l (%). Most unit values of EE and EC were obtained from Tavares [10] because they are closest to the Brazilian reality. For the values not provided in the Tavares [10] thesis, the software SimaPro [28] was used to calculate the LCA of the materials based on the Ecoinvent database [29]. Cumulative Energy Demand was used in SimaPro as an impact assessment method for calculating the Embodied Energy and the "selected LCI results", where the amount of CO$_2$ emitted was used to calculate the embodied carbon.

3.2. Envelope Performance according to the PBE Edifica

To determine the envelope performance based on the PBE Edifica, the simulation method described by the RTQ-R [30] was applied using the EnergyPlus 8.4.0 software [31]. For energy modelling, Euclid 0.9.0 [32] was used, a plug-in that employs SketchUp's drawing tools and creates.idf files for input in the EnergyPlus simulation.

A thermal zone was modelled for each extended stay environment (rooms and living room). Wet areas and common use areas were modelled as a single thermal zone. The zones have a solar orientation, geometric characteristics and thermal properties of the construction materials identical to the design.

For building 2, only the thermal zones of the first, middle and last floors were analysed. However, to obtain a more accurate result, the floors adjacent to the analysed ones were also modelled. The other floors were modelled as a single thermal zone.

Fig. 5 represents the energy model and the standard floor plan of the studied dwellings. Only the extended stay environments were analysed, that is, the rooms and living rooms.

Table 3 shows the physical properties of the building materials for the two buildings. The building materials were obtained from the design specifications and through visual recognition, following Giacomin [19].

The building performance was simulated in two situations, (a) naturally ventilated and (b) artificially cooled [30]. For the former situation, the number of cooling degree-hours (DH_C) per year is calculated with Eq. (1). The operating temperature is calculated with Eq. (2).

$$\sum (T_0 - 26\ ^\circ\mathrm{C}) \tag{1}$$

Where: T_O = operating temperature.

$$T_O = A.\ T_a + (1 - A).\ T_r \tag{2}$$

where

A = 0.5 (constant for air velocity less than or equal to 0.2 m/s);
T_a = ambient air temperature;
T_r = mean radiant temperature.

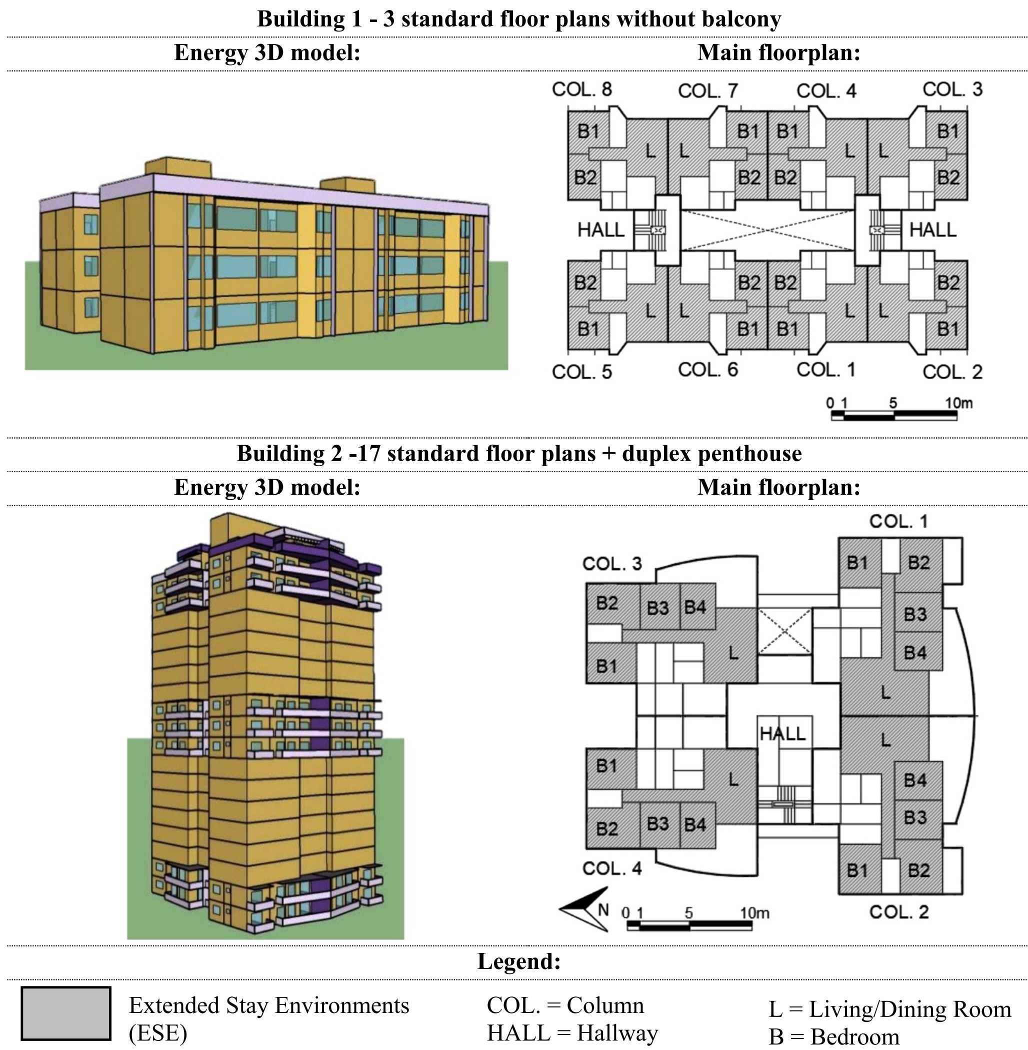


Fig. 5. Energy model and standard floor plan of the buildings.

Table 3
Properties of building materials.

Materials	Equivalent thickness (cm)	Conductivity (W/m K)	Equivalent density (kg/m^2)	Specific heat (kJ/kg K)	Thermal resistance (m^2 K/W)	Absorptance (α)
Plaster mortar	2.50	1.15	2000	1.00	_	Build. 1 – 0.34 (light colour) and 0.70 (dark colour) Build. 2 – 0.41[a]
Six-hole ceramic brick – 9 cm	1.50	0.90	1812	0.92	_	_
Concrete slab	Build. 1 – 10.00 Build. 2 – 18.00	1.75	2200	1.00	_	_
Fibre-cement roofing tile	0.70	0.95	1900	0.84	_	Build. 1 – 0.65[b] Build. 2 – 0.16[c]
Air gap (2–5 cm)	_	_	_	_	0.16	_
Air gap (> 5 cm)	_	_	_	_	0.21	_

Note:.
[a] Absorptance value weighted by façade area, considering 80% with α = 0.34 (ivory colour) and 20% with α = 0.70 (dark green).
[b] Absorptance similar to apparent concrete colour.
[c] The fibre-cement tile has a thermal treatment with white paint.

For the simulation in which the building is artificially cooled, the relative energy consumption required for refrigeration (C_R) is calculated and divided by the usable area of the environment. The capacity of the cooling system is automatically calculated by the simulation program, based on the parameters indicated in the RTQ-R [30]. For residential buildings, only the artificially cooled rooms from 9 p.m. to 8 a.m. are considered. At other times, the building is considered to be naturally ventilated.

Table 4 shows the parameters input into the EnergyPlus to simulate the efficiency of the envelope. Figs. 6 and 7 respectively show the

Table 4
Software input parameters.
Source:Brasil [30].

Item	Parameter	Value
Natural ventilation	Wind Speed profile exponent	0.33
	Discharge coefficient for opening factor 2	0.60
	Discharge coefficient for opening factor 1	0.001 kg/s m
	Air mass flow exponent when opening is closed	0.65
	Ventilation control mode temperature	20 °C(1)
People	Number of people	2 per bedroom
	Activity level in Living Room	108 W(2)
	Activity level in Bedroom	81 W(3)
	Residents' schedule	Fig. 6
Light	Watts per zone floor area – Living Room	6.0 W/m^2
	Watts per zone floor area – Bedroom	5.0 W/m^2
	Light schedule	Fig. 7
Electric appliances	Watts per zone floor area - Living Room	1.5 W/m^2
	Electric appliances schedule	On full time
HVAC – Cooling	Thermostat	24 °C
	Outdoor airflow rate per person	0.00944 m/s
	Supply fan operating mode	Continuous
	Supply fan total efficiency	70%
	Supply fan motor efficiency	90%
	Cooling coil gross rated COP	3.00 W/W

Note: (1) Automatic window opening control, which opens the windows when the internal ambient temperature is equal to or greater than the temperature indicated on the thermostat; (2) Produced heat of 60 W/m^2 for skin area equal to 1.80 m^2; (3) Produced heat of 45 W/m^2 for skin area equal to 1.80 m^2.

occupancy pattern and the lighting pattern of the ESE of both buildings. The results of the simulations were compared with reference values for the city of Vitória (ES), described in Table 5.

3.3. Operational Energy (OE)

To calculate the energy in the operation stage of the building, the following three scenarios of monthly consumption per housing unit (HU) were outlined: (1) 0–200 kW h; (2) 201–300 kW h; and (3) greater than 300 kW h. These profiles were based on the survey of ownership of appliances and use habits for dwellings located in the south-eastern region of Brazil (ELETROBRAS [34]). The number of housing units for each consumption profile depends on the area of the building, as described in Table 6 (ELETROBRAS [34]). The consumption of Building 1, despite measuring 58.8 m^2 per HU, was determined to be similar to that of a building with up to 50 m^2 per HU, due to its lower building standards. That is, for Building 1, 88% of the HUs consume up to 200 kW h monthly, 7.5% consume between 201 and 300 kW h, and 4.5% have a monthly consumption greater than 300 kW h. For Building 2, 41% of the housing units consume up to 200 per month, 19% consume between 201 and 300 kW h, and 40% of the apartments have a monthly consumption greater than 300 kW h.

Regarding the number of people per HU, the data collected by the City of Vitória were taken from the 2010 Census [35], which indicated that the average number of inhabitants per household in the Jardim Camburi neighbourhood is 2.7 people. Therefore, two inhabitants/HU were estimated for the consumption range 0–200 kW h, three inhabitants/HU for the consumption range 200–300 kW h and four inhabitants/HU for consumption exceeding 300 kW h.

To calculate the operational energy in the three scenarios, the energy consumption was divided into appliances, lighting, water heating and air conditioning.

Table 7 shows the estimated monthly appliances consumption for the residences across the three levels of energy consumption, based on appliances possession surveys (ELETROBRAS [34]). The appliances energy consumption was considered constant throughout the year.

The energy consumption of lighting was obtained by simulation, based on the standards established by the RTQ-R (Fig. 7) and an average consumption of 6 W/m^2 for the living rooms and 5 W/m^2 for the bedrooms. For lighting of wet areas, the same parameters of the living room were considered. It was considered that the lighting consumption results obtained by simulation refer to the higher consumption range. For the other ranges, the consumption was proportional to the number of residents.

According to the Southeast Region Report (ELETROBRAS [34]), the average bathing time for all levels of energy consumption is 10 min. Thus, to calculate the energy consumption for water heating, one shower per day per inhabitant for 10 min, was considered. In the case of device power, the same report indicated the use of power reduced 50% during the hottest months of the year, which, for the city of Vitoria, are January to April, November and December. From May to October, maximum device power is used.

For Building 1, which has electric showers, the device was estimated to operate with 5500 W at maximum power and 2750 W at reduced power.

Building 2 uses a gas heater with a flow rate of 31 l/min. To calculate the device power, a mean flow rate equal to half the flow capacity of the device was assumed, that is, 15 l/min or 900 l/hour. The difference in water temperature between the warmer and cooler months was based on the average ambient temperature in the two situations, namely, 25 °C in the warmer months and 20 °C in the cooler months. For the hot water temperature, the minimum temperature of the device was used for summer, and the maximum temperature was used for winter [36], which are 35 °C and 40 °C, respectively. That is, it was estimated that the water temperature difference in the warmer months is 10 °C and 20 °C in all other months. Therefore, the average useful power of the heater is 10.5 kW from January to April, November and December and 21 kW between May and October. Table 8 shows the power of water heater appliances during the warm and cold periods of the year.

Regarding air conditioning energy consumption, it was established that the consumption range between 0 and 200 kW h demonstrates the appliance is absent. The dwellings whose consumption range is

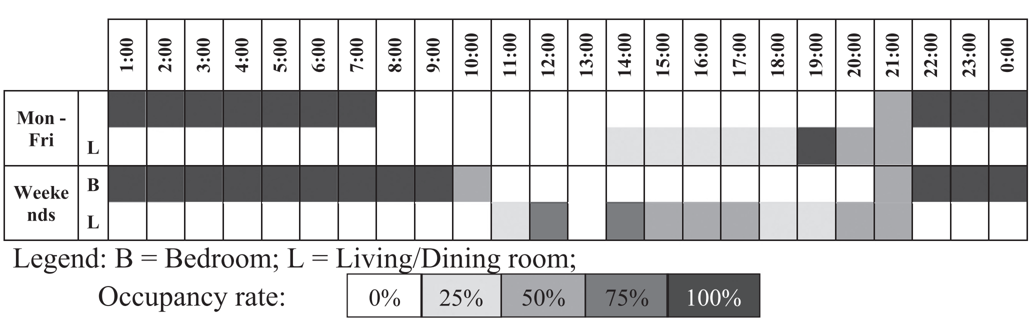


Fig. 6. Occupancy pattern of extended stay environments.
Source: Brasil [30].

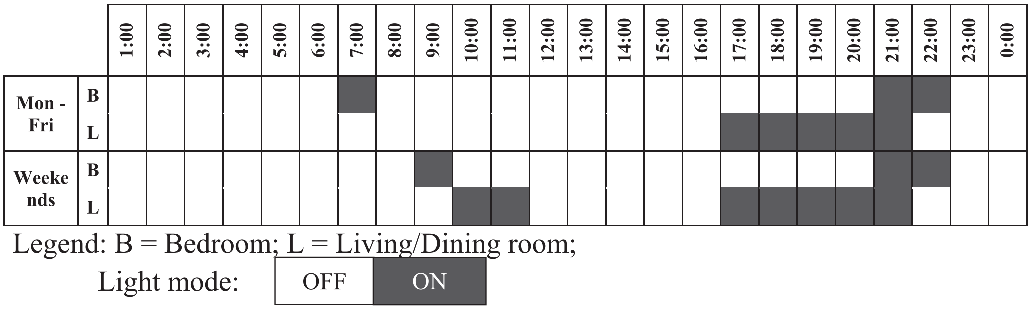


Fig. 7. Lighting pattern of the extended stay environments.
Source: Brasil [30].

Table 5
Reference values of DH_C and C_C for the city of Vitória (ES).
Source: PBE EDIFICA [33].

Efficiency	DH_C (h)	C_R (kW h/m^2 year)
A	$DH_C \leq 1847.60$	$C_R \leq 35.13$
B	$1848 < DH_C \leq 3895.27$	$35.126 < C_R \leq 53.58$
C	$3895 < DH_C \leq 5404.81$	$53.578 < C_R \leq 75.24$
D	$5405 < DH_C \leq 7255.43$	$75.241 < C_R \leq 92.94$
E	$7255 < DH_C$	$92.938 < C_R$

201–300 kW h have only one appliance in the largest room. For the consumption range greater than 300 kW h, air conditioning was assumed to exist in the two largest rooms. To calculate the consumption, the results obtained by simulation for the artificially cooled building were considered, whose use standards are described in Item 3.2 of this article.

For the energy required for cooking, 389.2 kW h was considered per person per year, based on national statistical data and the proportion of liquefied petroleum gas and natural gas used in the residential sector [2].

Considering the ratio of HU per consumption range established in Table 6, the annual calculation of energy consumption per building was multiplied by the lifespan of the building, that is, 50 years. To establish consumption in terms of primary energy, the total electric energy was multiplied by an index of 1.60 [37] and 1.10 for energy from cooking gas [38]. These indices refer to losses during the transformation and distribution of energy. In the case of CO_2 emissions, indices of 0.02125 $kgCO_2$/MJ for electricity [37] and 0.0642 $kgCO_2$/MJ for energy from natural gas [39] were used.

4. Results and discussion

The buildings were simulated for the following seven situations: (1) Existing building; (2) Replacing the traditional roof with the green roof; (3) Installation of reflective film on glass panes; (4) Shading of openings with brises; (5) Reduction of envelope absorptance; (6) Installation of ventilated façade; and (7) All retrofit measures combined. For each situation, the naturally ventilated and artificially cooled buildings were simulated. For the naturally ventilated building, we used cooled Degree-Hours (DH_C) to verify how the measures impact the internal temperature of the environment. For the situation in which the building is artificially cooled, in addition to verifying the labelling by calculating the relative cooling consumption (C_C), the air conditioning energy consumption was verified. To analyse the total life cycle energy consumption, the results were divided into pre-operational and operational stages.

4.1. Embodied Energy of materials

The EE values for Buildings 1 and 2 before any changes are 7.1 GJ/m^2 and 9.0 GJ/m^2, respectively, and the EC values are 491.8 kg CO_2/m^2 and 605.2 kg CO_2/m^2, respectively. The high EE value in Building 2 is due to the various finishing elements and installations with high unit values of embodied energy, such as aluminium and glass. According to Fig. 8, whereas in Building 2, the aluminium represents 10% of the IEE and 22% of the REE, in Building 1, the same material represents 5% and 14% of the IEE and REE, respectively. In the case of the REE (recurrent embodied energy), this value is significant for certain materials, often surpassing the IEE (initial embodied energy), such as paint and ceramic tiling. For both buildings, the loss associated with material waste during construction and maintenance processes constitutes approximately 10% of the total EE. The most significant loss values are for ceramic brick, steel and concrete.

Fig. 9 shows the embodied energy (EE) and embodied carbon (EC) of the existing building materials and after the implementation of the retrofit measures. When all retrofit measures are applied, the EE of Building 1 and 2 increases 13% to 8.0 GJ/m^2 and 4% to 9.3 GJ/m^2, respectively. In Building 1, the green roof had the greatest impact on the total EE due to the coverage extension and the REE and WEE values of the materials required for waterproofing. However, the ventilated façade generated the greatest increase in EC. In Building 2, among the retrofit measures, the ventilated façade installation had the highest values of EE and EC due to the extension of the façade and the volume of added material.

Table 6
Average energy consumption of houses in the southeast in relation to their built area.
Source: *ELETROBRAS* [34].

		Built area of housing unit			
		Up to 50 m^2 (Building 1)	51–75 m^2	76–100 m^2	101–150 m^2 (Building 2)
Monthly energy consumption	0–200 kW h	88%	72%	48%	41%
	201–300 kW h	7.5%	19%	28%	19%
	> 300 kW h	4.5%	9%	24%	40%

Table 7
Appliance monthly consumption by consumption range.

Appliances	Power (W)	Days of use/month	Average use per day (h)			Monthly average consumption (kW h)		
			0–200 kW h	201–300 kW h	> 300 kW h	0–200 kW h	201–300 kW h	> 300 kW h
Refrigerator	79.00	30	24.00	24.00	24.00	56.88	56.88	56.88
Vertical/horizontal freezer	66.04	30	0.00	0.00	24.00	–	–	47.55
Colour TV – 40"	83.00	30	2.50	3.75	5.00	6.23	9.34	12.45
Stereo	110.00	20	1.50	2.25	3.00	3.30	4.95	6.60
Electric iron	600.00	12	0.50	0.75	1.00	3.60	5.40	7.20
Washing machine	146.67	12	0.50	0.75	1.00	0.88	1.32	1.76
Computer	63.00	30	4.00	6.00	8.00	7.56	11.34	15.12
Microwave oven	1398.00	30	0.17	0.25	0.33	6.99	10.49	13.98
Blender	213.33	15	0.13	0.19	0.25	0.40	0.60	0.80
Mixer	150.00	8	0.17	0.25	0.33	0.20	0.30	0.40
Total monthly consumption of appliances (kW h)						**86.04**	**100.61**	**162.74**

Table 8
Power of water heaters during warm and cold periods of the year.

	Average power of electric shower (W) – Building 1	Average power of the gas heater (W) – Building 2
Cold months (May–October)	5500	2100
Warm months (January–April, November and December)	2750	1050

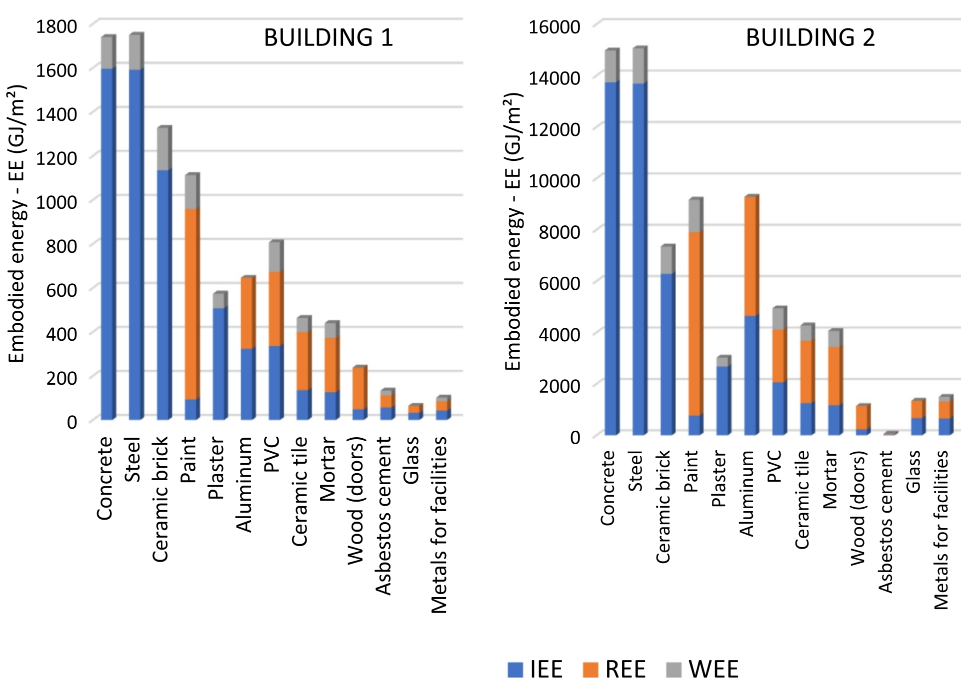


Fig. 8. EE for building materials. *Note: IEE = Initial embodied energy; REE = Recurrent embodied energy; WEE = Wasted embodied energy.*

4.2. Envelope performance according to the PBE Edifica

Regarding energy efficiency based on the PBE Edifica standards, Table 9 shows the envelope labelling of the existing buildings for the naturally ventilated and artificially cooled situations. Notably, the areas in a favourable position relative to the sun exhibit higher efficiency levels. The same applies to the case of the floors. The top floor, due to heat exchange through the roof, which in turn is exposed to the sun, has lower performance levels compared with other floors.

Fig. 10 shows the envelope labelling results for the naturally ventilated situation after including the retrofit proposals. The results refer to the worst-performing apartment column, which is column 3 in Building 1 and column 4 in Building 2. The retrofit proposals that yielded the greatest performance improvements of the buildings, according to the PBE Edifica standards, were the absorptance reduction and the ventilated façade. In the case of Building 1, both proposals raised all environments to performance level A, except for the living room in the top floor, whose reduction of the envelope absorptance, which includes the external walls and roof, proved to be even more efficient than the ventilated façade. The green roof, the reflective glass panes and the shading of the openings, though not greatly impacting the reduction of the DH_C, were sufficient to increase the labelling of the environments in level C to level B.

In the case of Building 2, which had already undergone heat treatment on the roof tiles, the green roof was not effective for reducing the DH_C or the relative cooling consumption (C_C), particularly in the top floor areas. In the case of shading the openings, in the environments with openings shaded by a balcony, the performance remained identical to that of the existing building because brises did not require installation. Although not significantly reducing DH_C, the adoption of

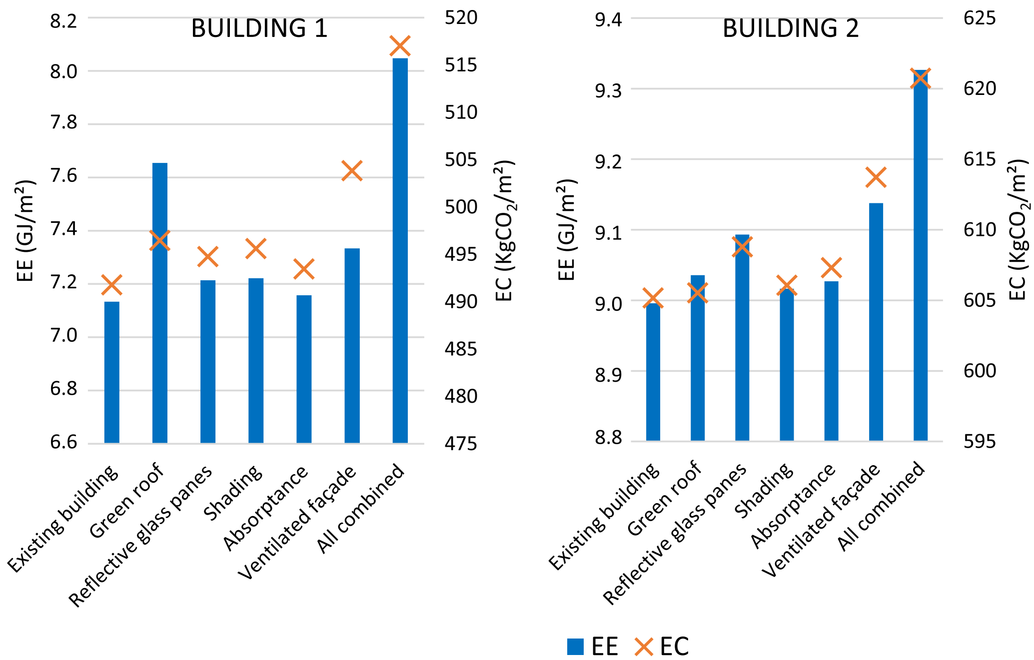


Fig. 9. EE/m^2 and EC/m^2 in the life cycle of Buildings 1 and 2. Note: *EE = Embodied energy; EC = Embodied carbon.*

reflective glass panes raised the labelling of zones that were at level C to level B.

After adopting all measures, most areas of both buildings reached performance level A in both simulated conditions.

4.3. Operational Energy (OE)

The OE analysis of existing buildings shows that Building 1 consumes 14 GJ/m^2, and Building 2, 11 GJ/m^2. According to Fig. 11, most energy in both buildings is consumed by appliances. In Building 1, the shower as a water heating system proved to be less efficient because it accounts for 20% of the total energy consumption and 14% of CO_2 emissions, while the gas system in the Building 2 accounts for 4% of the total energy consumption and 9% of total CO_2 emissions.

The air conditioning consumption is higher in Building 2. According to Table 6, 40% of the housing units (HU) in Building 2 have a monthly energy consumption of more than 300 kW h and therefore use air conditioning often in the two largest rooms. In Building 1, only 4.5% of the HU use artificial cooling in all rooms.

The energy/m^2 values for cooking and appliances in Building 2 were lower than in Building 1. For cooking, the energy consumption is related to the number of people, and Building 2 has fewer people per m^2. A fixed value was set for the appliances per housing unit. Thus, the energy consumption by appliances decreased as the area of housing increased.

The retrofit measures selected for this study only influenced energy consumption for air conditioners. According to Fig. 12, the changes in energy consumption were more significant in Building 2, whose energy consumption in the operational stage decreased 15%, from 11 GJ/m^2 to 9 GJ/m^2, after adopting all retrofit measures. By contrast, Building 1 reduced its energy consumption only 3% in the life cycle operational stage.

4.4. Total life cycle energy

The total life cycle energy is the sum of the embodied energy (EE) and operational energy (OE) for a fixed period of 50 years. Existing Buildings 1 and 2 respectively consume 21.0 GJ/m^2 and 19.8 GJ/m^2 of total life cycle energy, which generates emissions of 917.7 kgCO_2/m^2 and 938.4 kgCO_2/m^2. Fig. 13 shows the ratio of embodied and operational energy to the total consumed energy. Note that the EE has greater representativeness in the life cycle for Building 2 compared with Building 1 because Building 2 has greater quantities of elements with a high unit value of EE, such as glass and aluminium. The same trend was found in the study by Tavares [10], which, comparing the life cycle energy consumption in low-income single-family households with multi-family medium-income households, showed a lower proportion of EE in the former.

Tables 10 and 11 show the life cycle energy of Buildings 1 and 2, respectively. All retrofit measures increased EE through the addition of new materials. However, these additions generated savings in OE. For the measures that reduced the life cycle energy consumption, the payback time was calculated, that is, the operation time required to compensate for the embodied energy after implementing the retrofit measures.

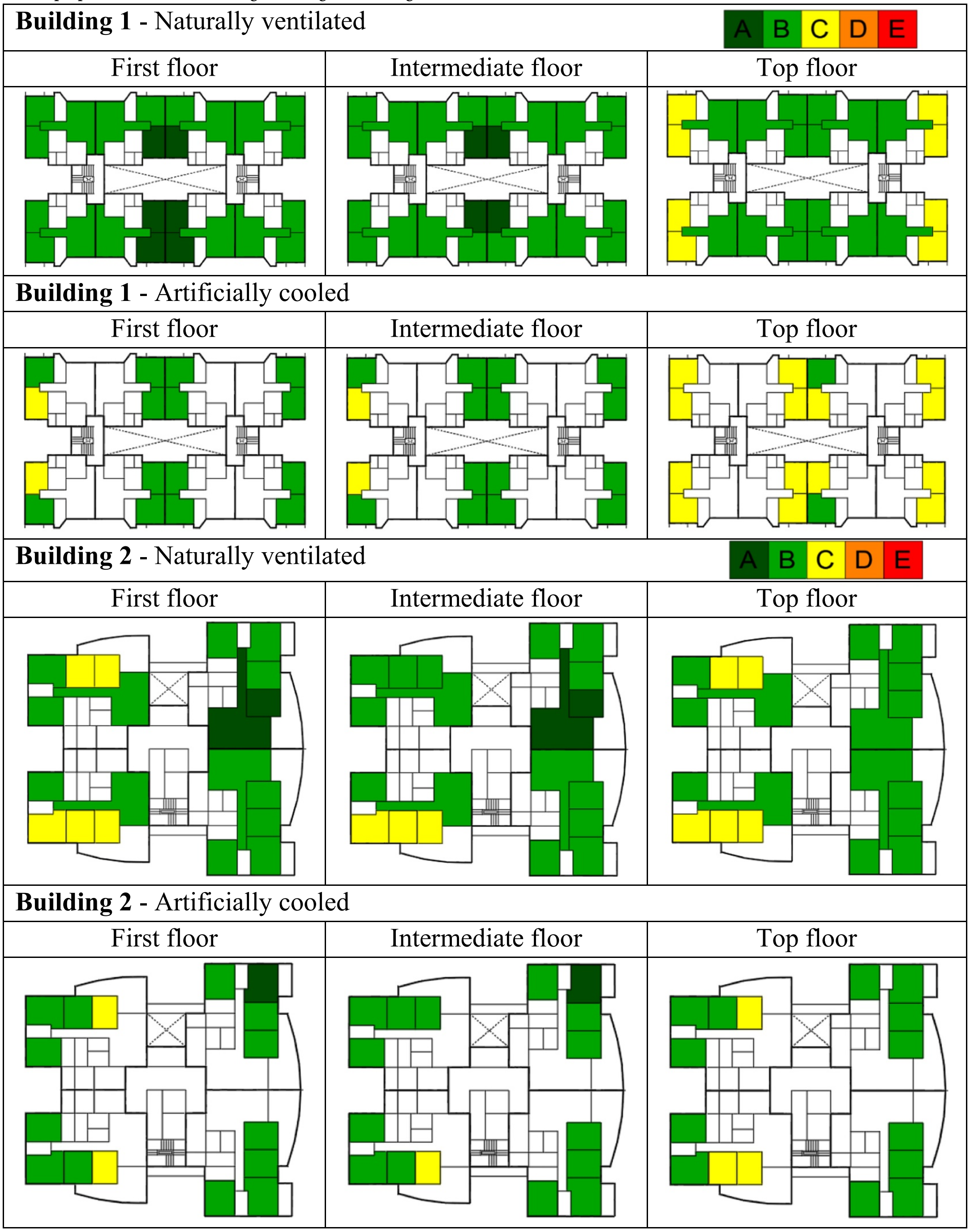
According to the results presented in Table 10, only the change in absorptance and the installation of a ventilated façade reduced the life cycle energy in Building 1, by 1% and 0.2%, respectively. However, the ventilated façade had a long payback time, making it unfeasible. The implementation of all retrofit measures was also not beneficial because it increased the life cycle energy consumption from 21.0 GJ/m^2 for the existing building to 21.5 GJ/m^2 for the building with all retrofit measures. This 2.4% increase was caused mainly by the green roof, which increased the life cycle energy consumption by 2.1%.

For Building 2, whose results are shown in Table 11, only the green roof did not create benefits for the life cycle. After adopting all measures, Building 2 increased its EE by 3.7% but decreased its OE by 14.7%. The life cycle energy consumption for the existing building and with all retrofit measures was 19.8 GJ/m^2 and 18.5 GJ/m^2 respectively, exhibiting a decrease of 6.4%. In terms of payback time, installing reflective glass panes results in a period longer than 20 years. However, the shading of the openings, the reduced absorptance and the ventilated façade showed similar values, approximately 6 years.

5. Conclusion

The present article analysed the life cycle of two typical neighbourhood buildings in the case of adopting retrofit measures. The embodied energy (EE) of the materials was calculated, corresponding to the sum of the Initial Embodied Energy (IEE), Recurrent Embodied

Table 9
Envelope performance of existing buildings according to the PBE Edifica.



Energy (REE) and Wasted Embodied Energy (WEE). In the operation stage, in addition to the operational energy (OE) consumed over a 50-year life cycle, the labelling of the envelope was analysed using the parameters of the PBE Edifica through the RTQ-R [30].

Compared with international references, the existing building has high values of embodied energy. According to Dixit et al. [40], the EE average is 5.5 GJ/m^2, with a standard deviation of 1.56 GJ/m^2. However, with regard to research in Brazil, Paulsen and Sposto [38] found a value of 7.6 GJ/m^2 for a typical single-family residence enrolled in the "Minha Casa Minha Vida" Program. Tavares [10] observed values in the same order of magnitude, yielding an average of 7.0 GJ/m^2.

The retrofit measures that increased EE were the green roof and ventilated façade. In the case of the green roof, the greater the ratio of the roof area to the built area of the building, the more the EE increased because the entire EE for green roof installation is on the rooftop. In addition, the waterproofing process, along with having a high IEE unit value (52.9 MJ/kg), has a high replacement factor (F_r) because it requires constant maintenance. Regarding the ventilated façade, which concentrates the entire EE of the envelope, the greater the ratio between the façade area and the built area, the greater the EE value added to the existing building.

Buildings 1 and 2 consume less operational energy than observed in international studies of residential buildings. Cuéllar-franca and Azapagic [41] found values ranging from 34 GJ/m^2 to 50 GJ/m^2 for typical residential buildings of England. This difference exists because Brazilian buildings do not use heating systems, and air conditioning is

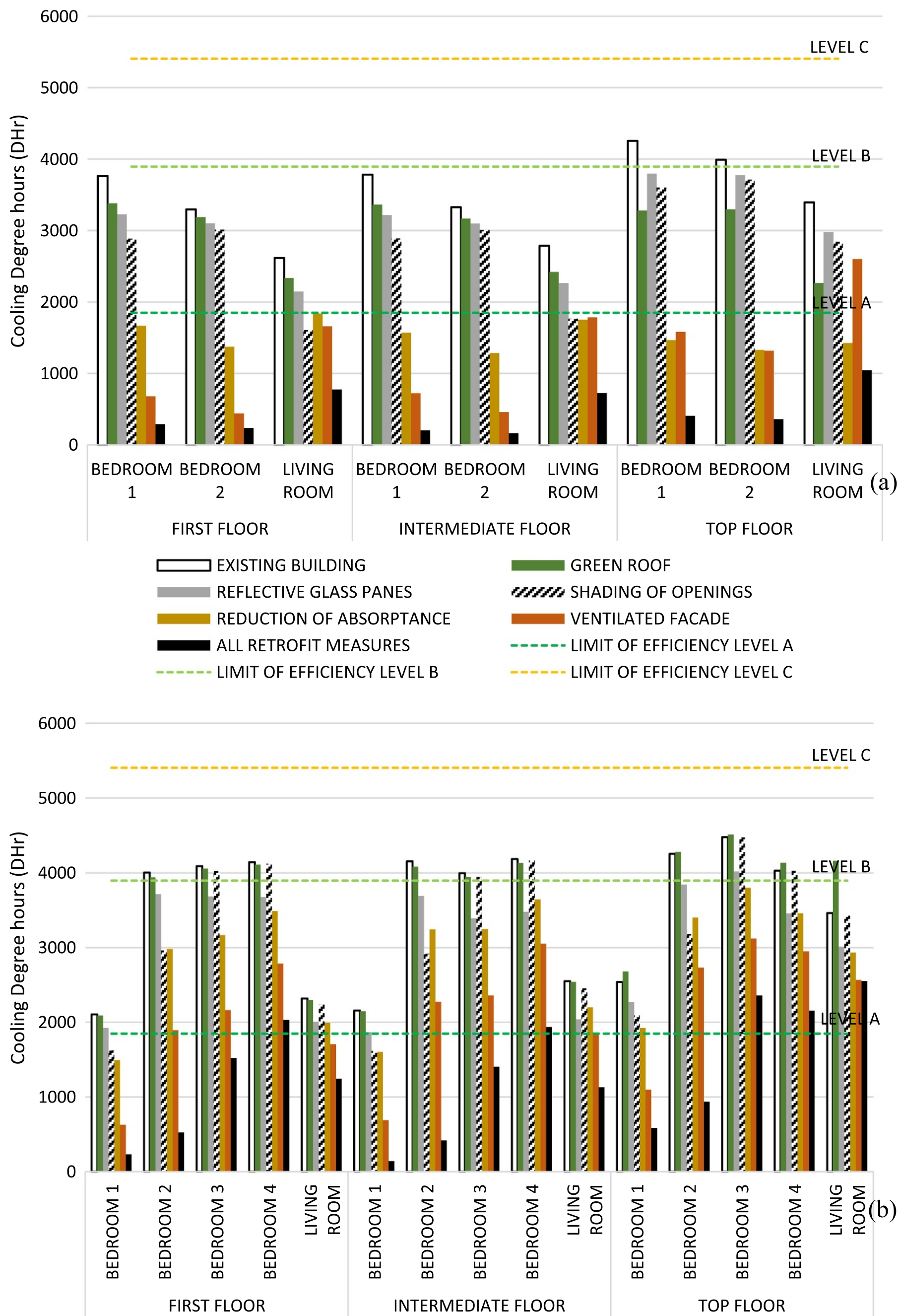


Fig. 10. Performance of the apartment column envelope with the lowest performance. *Note: (a) Building 1 – column 3; (b) Building 2 – column 4.*

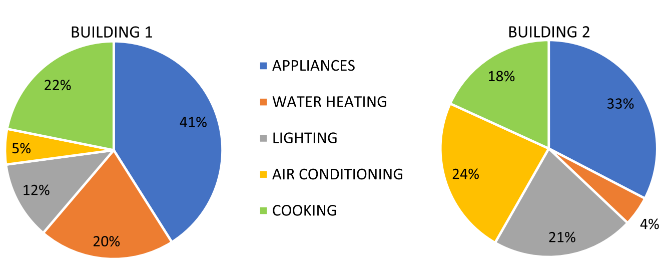


Fig. 11. Energy consumption in the operational stage.

an uncommon appliance in homes (ELETROBRAS [34]). Mechanical cooling of the thermal environment dictates a significant part of the Operational Energy (OE) on Building 2 (24%). One of the suggestions for future works is to analyse the impact of retrofit measures on passive cooling techniques, since the possession of air conditioning tends to increase, considering the reduction in price of this appliance. The change in absorptance and the installation of the ventilated façade were the most efficient measures, for both improving the envelope labelling and reducing energy consumption. In the case of Building 1, the light-coloured painting of the roof greatly reduced the DH_C of the areas on the top floor. The retrofit measure with the least effect on the OE was the green roof, which, despite having improved efficiency on the top floor of Building 1, had an opposite effect in Building 2 because the latter had already undergone heat treatment on the tiles. When tiles are given a heat treatment or have a low absorptance value, the green roof is an ineffective measure in the operational stage.

In the case of life cycle energy, both buildings consumed more energy during the operation. However, Building 2 exhibited a greater balance between embodied and operational energy. In Building 1, the

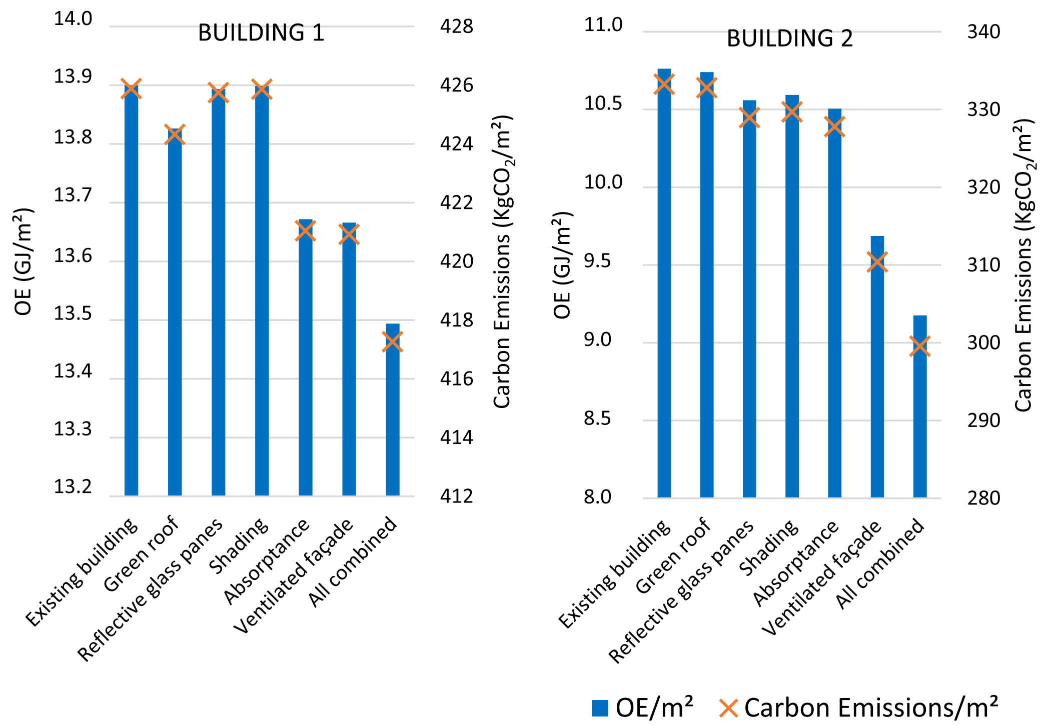


Fig. 12. OE/m^2 and CO_2/m^2 emissions in the life cycle of buildings 1 and 2. Note: *OE = Operational energy*.

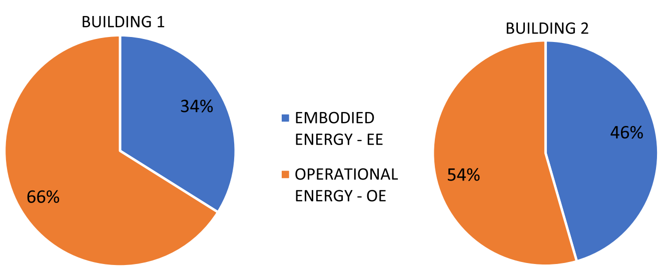


Fig. 13. Life cycle energy in existing buildings.

life cycle energy consumption was higher following the adoption of all retrofit measures, mainly after the installation of the green roof, because the energy embodied to the materials was insufficient to overcome the energy savings during the operation. Only the reduced absorptance was an effective change for decreasing the life cycle energy consumption, resulting in a payback time of 5.3 years. In Building 2, the retrofit measures reduced the life cycle energy consumption by 6.4%, yielding a payback time of 10.4 years, a long period compared with international studies [12,42]. When analysing the measures separately, the shading of the openings, the reduction of the absorptance and the ventilated façade were the most efficient measures.

Finally, the retrofit measures analysed in this article produced benefits in energy labelling and energy consumption during operation. However, when analysing the life cycle, certain measures were ineffective. This study stresses that the choice of retrofit measures to reduce the life cycle energy consumption should be preceded by extensive research, of both the materials to be added to the existing building and the energy consumption patterns of users. This paper reaffirms the importance of the decision making process, especially on the choice of materials, since it played a great part on buildings energy and carbon emissions. The decision should consider not only the manufacturing process of materials, but also the waste on the construction site, as well as their maintenance during the operational stage. The authors suggest, for future research, the development of tools that more extensively use Building Information Modelling (BIM) for LCEA, in order to visualize in a systemic way, the impacts of the design decisions throughout the construction process, from design to demolition, disposal and recycling of materials.

Table 10
Life cycle energy with the retrofit measures in Building 1.

	EXISTING BUILDING (GJ/m²)	GREEN ROOF	REFLECTIVE GLASS	SHADING	ABSORP-TANCE	VENTILATED FAÇADE	ALL RETROFIT MEASURES
EMBODIED ENERGY (EE)	7.1	▲ 7.3%	▲ 1.1%	▲ 1.2%	▲ 0.3%	▲ 2.8%	▲ 12.8%
OPERATIONAL ENERGY (OE)	13.9	▼ -0.5%	▼ -0.1%	▼ 0.0%	▼ -1.6%	▼ -1.7%	▼ -2.9%
LIFE CYCLE ENERGY	21.0	▲ 2.1%	▲ 0.4%	▲ 0.4%	▼ -1.0%	▼ -0.2%	▲ 2.4%
PAYBACK (YEARS)	–	–	–	–	5.3	42.8	–

Table 11
Life cycle energy with the retrofit measures in Building 2.

	EXISTING BUILDING (GJ/m²)	GREEN ROOF	REFLECTIVE GLASS	SHADING	ABSORP-TANCE	VENTILATED FAÇADE	ALL RETROFIT MEASURES
EMBODIED ENERGY (EE)	9.0	▲ 0.4%	▲ 1.1%	▲ 0.2%	▲ 0.4%	▲ 1.6%	▲ 3.7%
OPERATIONAL ENERGY (OE)	10.8	▼ -0.2%	▼ -1.9%	▼ -1.6%	▼ -2.4%	▼ -10.0%	▼ -14.7%
LIFE CYCLE ENERGY	19.8	▲ 0.1%	▼ -0.5%	▼ -0.8%	▼ -1.1%	▼ -4.7%	▼ -6.4%
PAYBACK (YEARS)	–	–	24.1	6.1	6.1	6.6	10.4

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Declarations of interest

None.

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